LOW SOLIDITY TURBOFAN

BACKGROUND OF THE INVENTION

The present invention relates generally to gas turbine engines, and, more specifically, to turbofan aircraft engines.

In a turbofan engine air is pressurized in a compressor and mixed with fuel in a combustor for generating hot combustion gases. A high pressure turbine (HPT) extracts energy from the combustion gases to power the compressor. A low pressure turbine (LPT) extracts additional energy from the combustion gases to power the fan disposed upstream from the compressor.

The primary design objective of aircraft turbofan engines is to maximize efficiency thereof for propelling an aircraft in flight, and correspondingly reduce fuel consumption. Accordingly, the various cold and hot section rotor and stator components which define the internal flow passages for the pressurized air and combustion gases, and which extract energy from those gases, are specifically designed for maximizing the efficiency thereof while correspondingly obtaining a long useful life.

The turbofan itself includes a row of large fan rotor blades extending radially outwardly from the perimeter of a supporting rotor disk. The fan is powered by the LPT for pressurizing the incident air for producing a majority of propulsion thrust discharged from the fan outlet. Some of the fan air is channeled into the compressor wherein it is pressurized and mixed with fuel for generating the hot combustion gases from which energy is extracted in the various turbine stages, and then discharged through a separate core engine outlet.

Turbofan engines are continually being developed and improved for maximizing their thrust capability with the greatest aerodynamic efficiency possible. Since the fan produces a substantial amount of thrust during operation, noise is also generated therefrom and should be reduced as much as possible consistent with the various competing design objectives.

For example, fan blades are typically designed for maximizing the aerodynamic loading thereof to correspondingly maximize the amount of propulsion thrust generated during operation. However, fan loading is limited by stall, flutter, or other instability parameters of the air being pressurized.

Accordingly, modern turbofan engines are designed with a suitable value of stability and stall margin over their operating cycle from takeoff to cruise to landing of the aircraft to ensure acceptable operation and performance of the engine without overloading the capability of the turbofan.

Furthermore, modern turbofan engines have relatively large diameter turbofans which rotate at sufficient rotary velocity to create supersonic velocity of the blade tips relative to the incident air stream. The blade tips are therefore subject to the generation of shock waves as the air is channeled and pressurized in the corresponding flow passages defined between adjacent fan blades.

Accordingly, each fan blade is specifically tailored and designed from its radially inner platform to its radially outer tip and along its circumferentially opposite pressure and suction sides which extend in chord axially between the opposite leading and trailing edges thereof. The pressure side of one airfoil defines with the suction side of an adjacent airfoil the corresponding flow passage from root to tip of the blades through which the air is channeled during operation.

Each airfoil is typically twisted with a corresponding angle of stagger from root to tip, with airfoil tips being aligned obliquely between the axial and circumferential directions of the fan.

During operation, the incoming ambient air flows at different relative velocities through the inter-blade flow passages from root to tip of the blades including subsonic airflow at the blade roots and radially outwardly thereof up to the supersonic velocity of the air at the blade tips in various portions of the operating range.

Fan stall margin is a fundamental design requirement for the turbofan and is affected by the aerodynamic fan loading, the fan solidity, and the fan blade aspect ratio. These are conventional parameters, with the fan loading being the rise in specific enthalpy across the fan blades divided by the square of the tip speed.

Blade solidity is the ratio of the blade chord, represented by its length, over the blade pitch, which is the circumferential spacing of the blades at a given radius or diameter from the axial centerline axis. In other words, blade pitch is the circumferential length at a given diameter divided by the number of blades in the full fan blade row. And, the fan blade aspect ratio is the radial height or span of the airfoil portion of the blade divided by its maximum chord.

Conventional experience or teachings in the art indicate that when inlet Mach numbers are sufficiently high that passage shock can separate the suction surface boundary layer of the air in the inter-blade flow passages, good efficiency requires that the solidity should be high to allow the flow to reattach.

In one exemplary or reference turbofan found in public use and on sale for more than a year in the USA, a large diameter turbofan having twenty-two fan blades in the full row has a relatively high solidity at the blade tips of about 1.29. These fan blades are used in a high bypass ratio turbofan engine with a bypass ratio over 7, with the corresponding pressure ratio over the fan blades being relatively high in value and greater than about 1.5. The large fan diameter effects supersonic velocity of the blade tips during operation which correspondingly generates normal shock waves at the airfoil tips during operation which affect performance.

Conventional design practice for turbofan efficiency and adequate fan stall margin typically require the relatively high tip solidity which is generally equal to the fan tip relative Mach number at the design point, such as cruise operation. In other words, the tip Mach number is suitably greater than one (1.0) for supersonic flow, and the fan tip solidity is correspondingly greater than one and generally equal to the tip relative Mach number for good designs.

The design considerations disclosed above are merely some of the many competing design parameters in designing a modern turbofan primarily for good aerodynamic performance and efficiency, as well as for good mechanical strength for ensuring a long useful life thereof. Each fan blade twists from root to tip, and the opposite pressure and suction sides thereof also vary in configuration to specifically tailor the flow passages from root to tip for maximizing fan efficiency with suitable stall margin and mechanical strength.

The resulting turbofan design is a highly complex design with three dimensional variation of the pressure and suction sides of the individual airfoils across their axial chord and over their radial span. And, the individual fan blades cooperate with each other in the full row of blades to define the inter-blade flow passages and to effect the resulting aerodynamic performance and stall margin of the entire fan.